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Catchment response to climate and land use changes in the Upper Blue Nile sub-basins, Ethiopia

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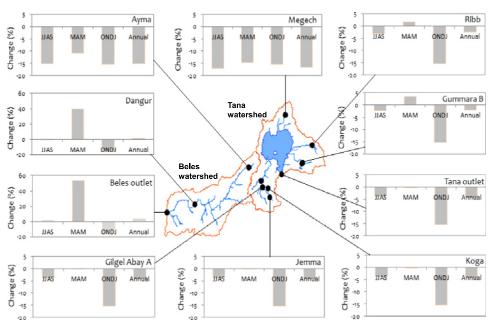
HIGHLIGHTS

- Climate in the study area is projected to be warmer and wetter in near-future.
- SWAT was used to assess the combined effects of climate and LULC change scenario.
- Climate scenario would intensify extreme flow in both sub-basins.
- LULC scenario might mitigate these extreme flows due to climate change.
- GCMs simulated rainfall underestimated historical rainfall during rainy season.

GRAPHICAL ABSTRACT



Changes in streamflow response to future land-use and land-cover (LULC) change scenario relative to that for 2010 LULC

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ABSTRACT

The impacts of climate and land development on streamflow and water balance components were analyzed in the Tana and Beles watersheds by using the Soil and Water Assessment Tool (SWAT). Streamflow response to simultaneous future land-use and land-cover (fLULC) and climate change (fCC) scenarios on the seasonal scale varied among the key water abstraction locations. The General Circulation Models (GCMs) average simulation of short-term climate indicated wetter and warmer climatic condition compared to that in the baseline period (1971/1980–2013). The near–future climate scenario would intensify extreme flow by increasing rainy season flow and reducing dry period flow. However, conversion of cultivation land on steep slope into forest might mitigate these extreme flows. At the outlet of Tana watershed, streamflow response would be amplified under concurrent scenarios of fLULC and fCC; but the streamflow would have an augmenting response at the outlet of the Beles watershed. Compared to response due to fCC alone, the streamflow and surface runoff components under combined fLULC and fCC scenarios would be alleviated in sub-catchments subject to conversion of cultivation in steep slope into forest land. The present results have significances for water resource management and land use planning in the Tana and Beles watersheds, and for other regions encountering identical pressures from climate change and LULC dynamics. In view of ongoing land use and climate dynamics, environmental policies must be carried out to cope with the potential changes of hydrologic regime. Moreover, catchment management should be adapted to changing hydrological regimes at different water abstraction points.

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1. Introduction

Land degradation as a threat to food security is a center of much attention globally, and particularly in developing countries, which rely on agricultural production for their economic growth and nations livelihood. Soil erosion by water is the dominant threat to 56% of the global area affected by soil degradation (Oldeman et al., 1994). Deforestation and over-exploitation of natural vegetative cover for domestic use are also the most causative factors for soil degradation. Soil degradation by erosion has both on-site and off-site effects (Tamene and Vlek, 2008). On-site effects of soil erosion imply nutrients loss, decline of rooting depth, and water storage capacity due to topsoil removal, and ultimately reduced land productivity. On the other hand off-site effects of soil erosion manifest in downstream flooding, sediment load in rivers, and reduction of storage capacity of dams due to siltation which ultimately affects energy generation and food production.

Climate, land-use and land-cover changes are among the main drivers of land degradation. It is especially aggravated if land-use and land-cover changes represent environmental land use conflicts, whereby the new use deviated from land capability (the natural use determined by soil characteristics and catchment parameters like slope, drainage density, etc.). In these cases, land degradation can be severely amplified (Pacheco et al., 2014). Climate change and variability effect land degradation by facilitating soil erosivity, especially that intensive rainfall accelerates soil erosion in bare vegetation cover. Runoff generation is a key process in land degradation, resulting in soil erosion and affecting the hydrological regime of the watersheds (Descheemaeker et al., 2006). Thus, understanding how climate change and land-use and land-cover (LULC) dynamics influence the variations in water resources/basin hydrology is vital for sustainable land and water resources management, which eventually reduce land degradation. Modeling studies (e.g. Tu, 2009; Kim et al., 2013; Wang et al., 2014; Fan and Shibata, 2015; Yin et al., 2017) on the combined influences of climate change and LULC dynamics have indicated that either change may be more considerable based on scenario assumptions and watershed characteristics.

In addition, the two types of changes may either augment or lessen the effects of one another on different spatio-temporal scales. The influence of climate change on catchment hydrology may result from spatio-temporal precipitation shifts, changes in evapotranspiration due to rises in temperature, and increase in extreme climatic events (Lahmer et al., 2001). Although less studied, the climate change impacts on catchment hydrology can even result in significant lowering of water table levels and base flows, with negative consequences for crop irrigation and groundwater supply to populations (Santos et al., 2014). Commonly, paired catchments, statistical analyses, and modeling approaches have recently been applied to know how climate change and LULC dynamics contribute to changes in water balance or basin hydrology. The paired catchment method is not applicable for large catchments due to unavailability of two similar large watersheds (Li et al., 2009). The statistical approach analyzes the hydroclimatic trends at monitoring stations (Bewket and Sterk, 2005); however, it fails to capture the physical processes in the watershed. In view of this, a spatially distributed hydrological model is considered as the most suitable method for determining the extent of influences of future climate combined with LULC changes. Physically based hydrological models have also been applied to quantify the relative effects of climate change and LULC on catchment hydrology (e.g. Schilling et al., 2008; Ma et al., 2009).

Many previous studies have examined the combined effect of climate and LULC changes on hydrology in different parts of the world (e.g. Tomer and Schilling, 2009; Tu, 2009). The outcomes of these studies (e.g. Choi, 2008; Kim et al., 2013) revealed that climate change was more dominant than LULC change in influencing the catchment hydrological regime. Due to the dissimilarity of the climatological and different physiographical conditions, climate and LULC change impact studies on water resources usually have a local to regional nature (Roosmalen et al., 2009).

One of those regions which reflect extensive LULC changes is the Upper Blue Nile Basin. As the economy of the region mainly depends on crop production, which in turn mainly depends on availability of water resources, the basin is very sensitive to rainfall-runoff generation. Crop cultivation by rainfall is the major source of food production in the study region, but its productivity is declining due to land degradation (Taddese, 2001). Small meteorological changes can lead to in comparatively large changes in the Blue Nile streamflow and water availability (Beyene et al., 2010). Besides, cultivation on steep slope coupled with intense rainfall might increase surface runoff, which in turn might accelerate land degradation. Streamflow response to environmental changes at key water abstraction points (currently operational, under-construction, and proposed water resource projects) in the watersheds is not well addressed. As the principal supplier to the Nile flow, the Tana and Beles watersheds (Fig. 1) response to environmental change (including LULC and climate change) is crucial for the Nile River flow in general, and the catchments in particular. However, previous studies in this region have usually focused on separate impacts of either climate change (e.g. Abdo et al., 2009; Beyene et al., 2010; Taye et al., 2011; Hadgu et al., 2015; Haile and Rientjes, 2015; Gebremedhin et al., 2017; Gizaw et al., 2017) or LULC change on hydrology (e.g., Rientjes et al., 2011; Tekleab et al., 2014; Welde and Gebremariam, 2017). Having separate studies of LULC or climate changes does not completely answer the questions as to the resulting influences on water resources. It is, therefore, crucial to consider both climate change and LULC dynamics and to evaluate their relative influence to hydrologic change.

The objectives of this study are: 1) to examine the response of hydrological processes to LULC and/or climate changes at the Tana and Beles watersheds; 2) to differentiate the impacts of LULC and/or climate changes on streamflow and hydrological components at key water abstraction points and watershed outlets. Since General Circulation Models (GCMs) are the key sources of projected climatic data applied to assess the effects of climate change on catchment water balance, this study utilizes aggregated GCMs outputs from the fifth Assessment Report (AR5) of the IPCC. AR5 adopted new scenarios, known as representative concentration pathways (RCPs), depending on different technical progresses. The RCPs are a group of greenhouse gas concentration and emissions pathways formed to provide interactive approach to climate change studies (Moss et al., 2010; Van Vuuren et al., 2011). RCP 6.0 is an intermediate pathway in which radiative forcing is maintained at approximately 6 W/m^2 after 2100.

2. Description of the study area

The Tana and Beles watersheds comprise the source of the Upper Blue Nile (Fig. 1). The two watersheds are joined through a Tana-Beles tunnel. There are three seasons in the study area: The main rainy season, which refers to the months June to September; the small rainy season that lasts from March to May; and the dry season, which lasts from October to February (NMA, 1996). The study region has been threatened by land degradation caused by deforestation, expansion of cultivation land, overgrazing and untenable use of land and water resources (Hurni, 1990). Expansion of cultivation into steeper lands and former forests provokes soil erosion and shortage of fuel wood. Crop cultivation by rainfall is the major source of food production in the study region. During the years when the rainfall is below average, crop yield reduction or total crop failure as well as power interruptions are common and have serious impact on food and energy security. Therefore, irrigation development and hydropower generation are considered a basis of the food and energy security in the study region. As a result, the government of Ethiopia has realized the importance of hydropower and small-scale irrigation projects (key water abstraction points in Fig. 1) and catchment management projects in the study area. The major LULC classes in the Tana sub-basin is cultivation land while that in the Beles sub-

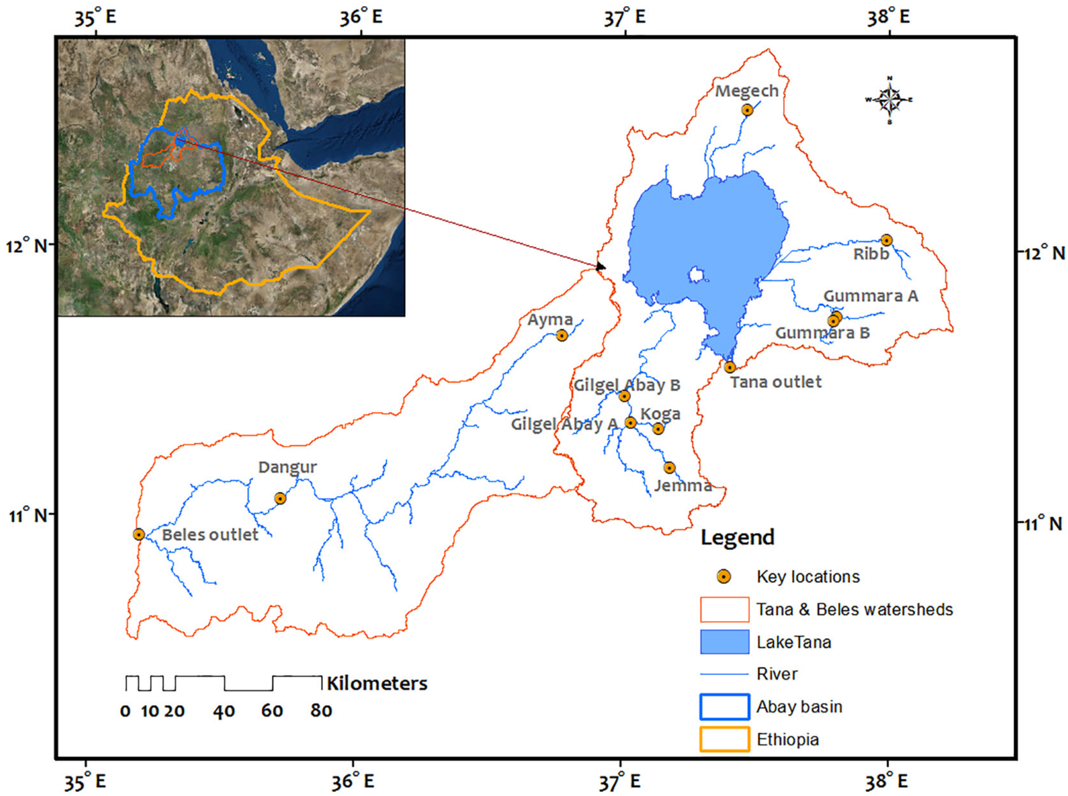


Fig. 1. Study area with water abstraction points and watersheds outlets.

basin is cultivation land followed by woodland (Woldesenbet et al., 2017a).

3. Data and methodology

3.1. Available data

This study applied calibrated and validated Soil and Water Assessment Tool (SWAT) model using a digital elevation model (DEM), soil data, LULC maps and meteorological data as input (Woldesenbet et al., 2017a). For detail descriptions of the LULC classification and hydrological model set-up, please refer to Woldesenbet et al. (2017a) while for climatic data see Woldesenbet et al. (2017b). In addition, for data and web sources used in this study please see Table S1.

3.2. Scenarios of climate and land-use and land-cover changes

3.2.1. Climate change scenario

The selection of emission scenario is less significant for the near-term climate projections (Praskievicz and Chang, 2009; Roosmalen et al., 2009), meaning that the choice among RCP2.6, RCP4.5, RCP6.0 and RCP8.5 concentration pathways is not vital for short-term projected climate data (2016–2030) in this study. Therefore, RCP 6.0 scenario, which is next to business as usual, was considered herein. Due to their coarse resolutions, the outputs from GCMs are almost never in a form that can be used directly to drive hydrological models. Downscaling the outputs from coarse-scaled GCMs to higher spatio-temporal resolutions is therefore vital. In this study, future climate scenario (RCP 6.0) was retrieved from MarkSimGCM interface (gisweb.ciat.cgiar.org/MarkSimGcm/). MarkSimGCM can be used to downscale outputs from GCMs and generate daily future temperature and rainfall data at a specific site (Jones and Thornton, 2013). The method uses a combination of empirical downscaling (interpolation of GCMs output), climate typing and weather generation. Menzel and Bürger (2002) describe how “weather type models utilize a finite set of specific circulation patterns [that] tend to persist for a certain amount of time. Within such a regime, daily precipitation is [modeled] stochastically using some form of weather generator with regime-dependent parameters”. The main advantage of a weather-typing scheme is that the local variables are closely linked to global circulation (Chen et al., 2011). Note, however, that the method inevitably presumes that climatic change will not bring in any new weather type (Bronstert et al., 2002), at least in the near-future term as is the case in this study.

MarkSimGCM is an improved version of MarkSim (Jones and Thornton, 2000). The general outline of the analysis in MarkSimGCM is as follows (Jones and Thornton, 2013). First, data from the GCMs for five time periods: 1991–2010, 2021–2040, 2041–2060, 2061–2080 and 2081–2100, for mean monthly total precipitation and daily air temperatures were obtained. Mean monthly climatologies were calculated for each time period and for each variable from the original daily data generated by each GCM. These mean monthly fields were interpolated from the original resolution of each GCM to 0.5 latitude–longitudes using conservative remapping (Jones, 1999). Second, monthly climate anomalies (absolute changes) were calculated for monthly total rainfall, and mean daily maximum and minimum temperatures, for each time period relative to the reference climatology obtained from WorldClim (1961–1990) (Hijmans et al., 2005). Third, a functional relationship was fitted to the climate projections for the variables of interest over time. Fourth-order polynomials were fitted throughout. Finally, the polynomial coefficients were condensed into a data-file structure for ready access on a pixel-by-pixel basis (at a resolution of 30 arc-min) for use in succeeding activities, i.e. downscaling the anomalies to a higher resolution, and then generating daily rainfall and temperature data using a stochastic daily weather generator. MarkSim has been designed specifically for use in the tropics, where data are mainly scarce. It has the ability to produce climate variables (rainfall, and minimum

and maximum temperatures), which are the principal data requisite for most hydrological models, such as SWAT. In addition, MarkSim has been commonly applied in East Africa, and apparently offers a reasonable simulation of daily temperatures and rainfall distributions (Lobell and Burke, 2010). It has been demonstrated to produce patterns of rainfall variability over East Africa realistically for applications in agriculture (Dixit et al., 2011). MarkSimGCMs downscaled climate data from the Fifth Assessment Report (CMIP5) were also used in northeast Ethiopia to assess climate change impact on crop production and to suggest management options (Mohammed et al., 2016; Mohammed et al., 2017). The GCMs selected in MarkSimGCM to generate the RCP6.0 scenario are indicated in Table 1. Even though it has been substantially tested (Jones and Thornton, 2013), MarkSimGCM simulations were compared with observed historical data from three weather stations in the present study. For each station, Kolmogorov-Smirnov and median rank tests were applied between MarkSimGCM generated rainfall and temperatures, and historical data for the period 1980–2005. The projections for temperature and rainfall changes for a given emission scenario are known to differ significantly among GCM models (Fowler and Ekström, 2009). Therefore, the ensemble average of all the seven GCMs for each weather station over the period 2016 to 2030 was used to run the hydrologic model. The downscaled future climate data from CIMP5 are archived at MarkSimGCM from the year 2015 onwards. To avoid additional uncertainty in the data due to bias correction (Teutschbein and Seibert, 2012), the downscaled data were not bias-corrected before being deployed to the hydrological model.

3.2.2. LULC change scenarios

For providing food and energy security, the Ethiopian government has been building smaller to mega dams in the Upper Blue Nile basin. However, erosion and sedimentation are considered as two of the factors leading to siltation of reservoirs. The erosion rates were higher from cropland than the averages for all lands in the study region (Haregeweyn et al., 2006) due to cultivation on steep slopes. There is a strong commitment from the government to tackling erosion and sedimentation, as well as rehabilitating degraded lands. One of the plausible measures for the future LULC map could be converting cultivation land on steep slopes higher than 10% to forest land in the Tana watershed, and to forest and/or woodland in the Beles watershed based on 2010 historical LULC maps. In addition, existing and planned irrigation schemes, including reservoirs, could be incorporated in the future land-use and land-cover scenario. Forest and woodland expansion can also be used for fuel wood and carbon sequestration. The final LULC map was used as an input in a calibrated and validated SWAT model to simulate the future streamflow and water balance components. The proportional extent of different LULC classes for future LULC scenario is shown in Table 2 and Fig. 2.

3.3. Model and simulations

GCMs are main sources of projected climatic data used to evaluate precipitation shift, temperature increase, or changes in meteorological events. Even though the modeled changes in watershed hydrology may be small, the choice of short-term scenarios avoids too important uncertainties in climate change: human behavior and policy choices. It is difficult to develop realistic land use and world market scenarios for a period of >20 to 30 years (Roosmalen et al., 2009). For this reason, short-term scenarios from 2016 to 2030 were considered in this study. Simulations based on altering LULC for the same climatic condition was applied to evaluate the impact of LULC on streamflow and water balance components.

On the other hand, the impact of climate change on streamflow and water balance components was assessed without altering LULC. Differences between the outcomes from these runs and a control run revealed the effect of changes in either the LULC or climate on streamflow and water balance components. The control run was a simulation using 2010 LULC and historical climate data. Results of changes in both LULC and climate from those used in the control run described the combined influences of both climate and LULC changes on catchment hydrology (See e.g. Lahmer et al., 2001; Guo et al., 2008). Following the calibration, all the model parameters were held constant for modeling future conditions. However, future climate and LULC changes may possibly alter the model parameters (Vaze et al., 2010). The responses of catchment hydrology to LULC and climate changes were evaluated using the SWAT, and the impacts of a single factor, i.e. LULC or climate change, on hydrological regime was distinguished according to Ma et al. (2009). In this study, four simulations were carried out to assess three different scenarios, i.e. the impacts of future climate change alone (fCC), future LULC change only (fLULC) and future climate and LULC changes combined (fLULC and fCC):

- Simulation 1 (reference) using 2010 LULC and climate data from 1981 to 2013 for the Beles, and from 1971 to 2013 for the Tana, watershed;
- Simulation 2 (fLULC) using fLULC map under 1971/1981–2013 climate data;
- Simulation 3 (fCC) using 2010 LULC map under 2016–2030 climate data;
- Simulation 4 (fLULC and fCC) using fLULC map under 2016–2030 climate data.

Table 2
Proportional extent of current and future LULC in Tana and Beles sub-basins.

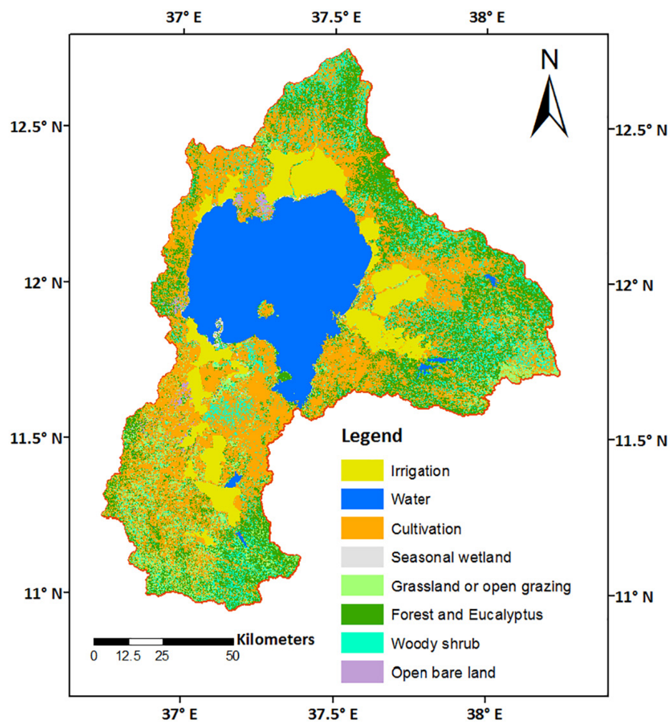
LULC Tana	LULC 2010 (%)	fLULC (%)	LULC Beles	LULC 2010 (%)	fLULC (%)
Cultivation	61.9	36.3	Cultivation	42.0	18.7
Forest and eucalyptus	2.4	19.5	Grassland	2.4	2.8
Woody shrub	8.2	7.2	Forest	8.2	17.0
Water	21.8	24.2	Woodland	21.8	33.3
Barren	0.2	0.1	Savannah	0.2	4.5
Grassland	5.7	4.5	Water	5.7	0.0
Irrigation (maize)	–	8.3	Irrigation (sugarcane)	–	23.6

Table 1
Selected GCMs from MarkSimGCM.

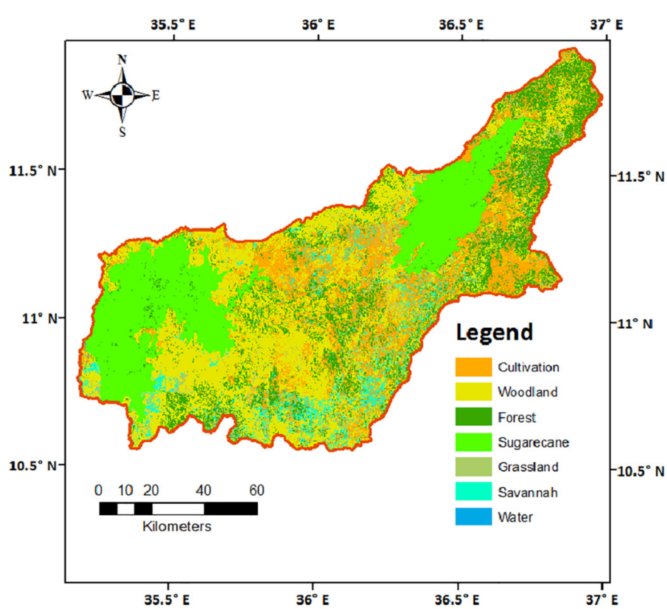
	Model	Institution	Resolution, latitude × longitude in degrees
1	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization and the Queensland Climate Change Center of Excellence	1.875 × 1.875
2	GLFD-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 × 2.5
3	GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 × 2.5
4	HadGEM2-ES	Met Office Hadley Center	1.2414 × 1.875
5	IPSL-CM5A-MR	Institute Pierre-Simon Laplace	1.2587 × 2.5
6	MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	1.4063 × 1.4063
7	MRI-CGCM3	Meteorological Research Institute	1.125 × 1.125

3.4. Data analysis

The impact of future LULC change alone on the basin hydrology was evaluated by comparing simulations 2 and 1, assuming the reference climate remains unchanged. To assess climate change impacts alone, simulations 3 and 1 were compared, assuming LULC remain unaltered. Combined impacts of climate and LULC changes on hydrological regime were evaluated by comparing simulations 4 and 1. The extent to which future climate change impact might be either mitigated or amplified due to future LULC scenario was evaluated by comparing simulations 4 and 3. To evaluate the combined effect of climate and LULC changes, the average values of the simulated water-balance components and streamflow under both fLULC and fCC scenarios for the future period (2016–2030) were compared to the current conditions in the baseline period, i.e. 1971–2013 for the Tana watershed and 1981–2013 for the Beles watershed. In addition, the statistical differences in median and distributions between simulations 2 and 1 as well as simulations 3 and 4 were evaluated using the median test and two-sample Kolmogorov–Smirnov test, respectively at 0.05 significance level (Table S2).



a)



b)

Fig. 2. LULC map including existing and planned irrigation schemes (a) for Tana and (b) for Beles watersheds.

4. Results

4.1. Future versus baseline climate

The Kolmogorov-Smirnov and median rank tests between MarkSimGCM generated and the observed rainfall and temperatures indicated that none of the GCM outputs for historical periods had similar distributions or medians (Tables S3 and S4). Furthermore, most of the GCMs underestimated the main rainy season and annual rainfalls, and overestimated temperatures during the base periods for all meteorological stations under consideration. Most GCMs underestimate the observed annual total rainfall during the historical period 1980–2005. Haile and Rientjes (2015) also indicated that the annual rainfall was underestimated by multiple RCMs' models initiated by the Coordinated Regional Climate Downscaling Experiment (CORDEX) in the Upper Blue Nile basin. However, GCMs' simulated monthly rainfall overestimated the observations in the months of the small rainy season (Fig. 3). The GCMs overestimated the observed maximum and minimum temperatures values during the base period (Fig. 3). As shown, GCMs overestimated the observed maximum temperature particularly in June, July, August and September while slightly under-estimated in November and December at the Bahir Dar and Gondar stations. In addition, the simulated streamflow using historical GCM simulated temperatures and rainfall as inputs to the hydrological model is compared to the observed discharge (Fig. S2).

The simulated results for fCC showed that all hydrological components would increase compared to the baseline period due to an increase in rainfall in the main rainy season and on the annual scale for the Tana watershed (Fig. 4). During the small rainy season, surface runoff, lateral flow, groundwater flow, percolation and water yield might decrease compared to those in the reference period. The decrease in hydrological components is attributable to a decrease in rainfall. Actual evapotranspiration would be lower than that of the baseline period in the small rainy season and the dry period (Fig. 4) due to a shortage in soil moisture as a result of reduced rainfall, even though potential evapotranspiration would be higher than that in the baseline period. Dry season water balance components might be reduced due to the fCC scenario except for groundwater and potential evapotranspiration.

In the Beles watershed, annual and seasonal total rainfalls would be higher than that in the reference period. As a result, basin-scale surface runoff, groundwater flow, lateral flow, water yield, percolation and actual evapotranspiration would increase (Fig. 4). Similar to the scenario in the Tana watershed, the rainfall in small rainy season might decline due to fCC. All hydrological components, except potential evapotranspiration in dry periods would decrease under fCC scenarios. In general, the hydrology of the sub-basins would be dominated by changes in rainfall than by temperature (rainfall-dominant watersheds).

Table 4 shows the result of the annual streamflow response to fCC scenarios at the Tana and Beles watershed outlets as well as at key water abstraction. It can be seen that annual and main rainy season streamflow at all locations would increase due to increased rainfall in both watersheds. But dry period average streamflow for fCC scenario might either decrease or remain unchanged mainly due to higher evapotranspiration.

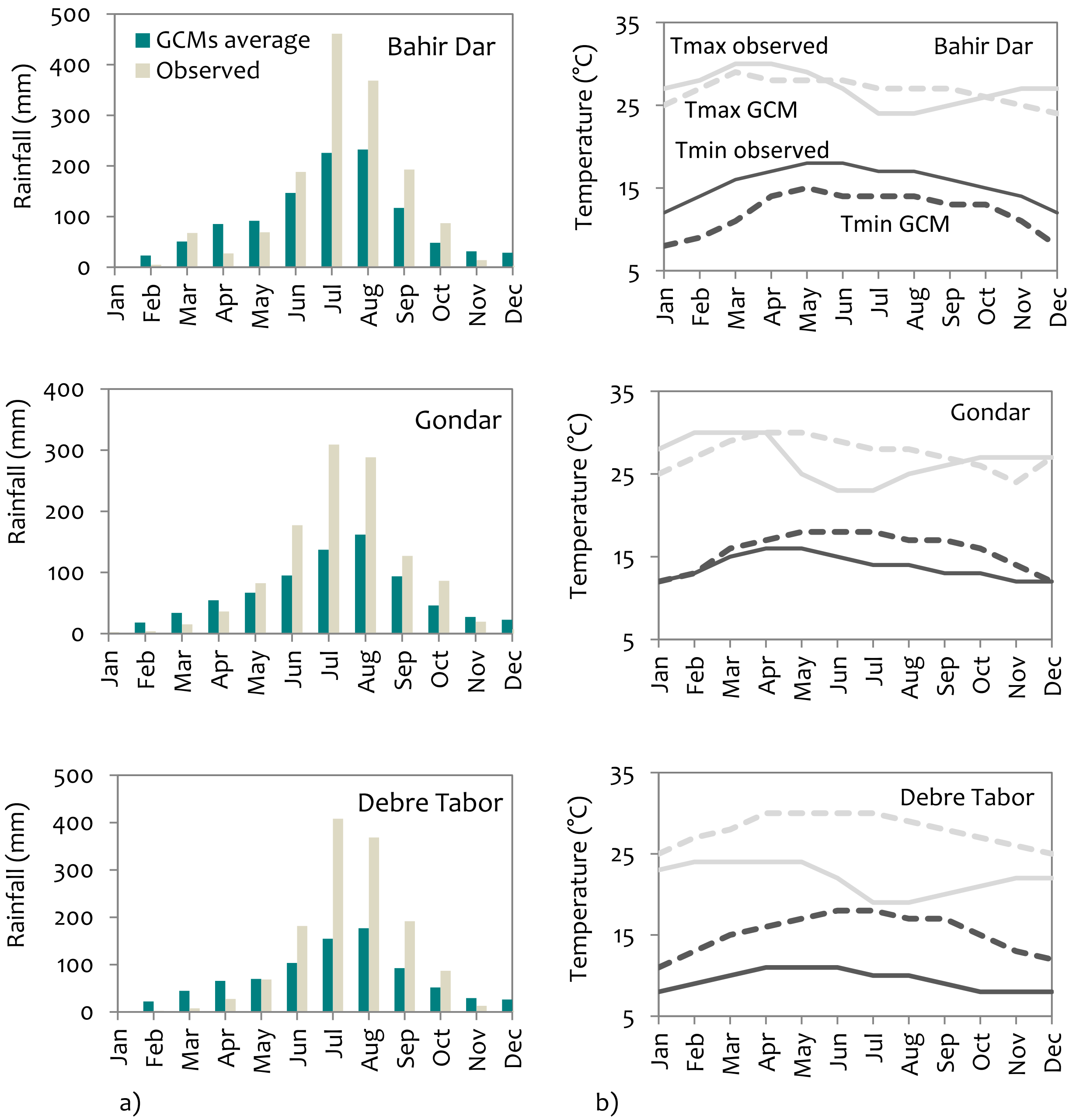


Fig. 3. Comparison between GCMs average and observed monthly a) rainfall and b) temperatures for selected stations during the historical period (1980–2005).

4.2. Future versus current LULC impacts

Fig. 3 shows that surface runoff component and water yield to streamflow might reduce on seasonal and annual scales due to future LULC scenario compared to that in the baseline period in the Tana watershed. On the other hand, lateral flow, groundwater flow, percolation, and actual evapotranspiration might increase due to future LULC scenario. These impacts would be due to a decrease in cultivation land coupled with an increase in forest land resulting from the afforestation scenario.

In the Beles watershed, surface runoff, groundwater and percolation might decrease for the future LULC scenario compared to the baseline period (Fig. 4 and Table 3). This response is opposite to that in the Tana sub-basin, mainly due to varied net changes in the future LULC scenario. There would be net loss in cultivation land and gain in forest land in the Tana watershed while in the Beles watershed, there would be net gain in forest and woodland coverage (Table 2). The loss in cultivation land in the upstream of the Beles watershed might be compensated by the gain in new irrigation land in the downstream. It is simulated that actual evapotranspiration would increase in the Tana and Beles watersheds, mainly due to a net increase in forest and/or woodland in the future LULC scenario.

At the Tana watershed outlet, the simulated annual and seasonal streamflow for future LULC scenario (QfLULC) would be significantly lower than that for the current LULC (Q2010LULC) (Table 4 and Fig. 5). The main contributor to the reduction of streamflow for future scenario would be a decline in the surface runoff component (due to reduction in cultivation land) coupled with increased actual evapotranspiration, particularly in the main rainy season when the moisture is abundant. The main rainy season and annual streamflows have shown higher percentage changes than small rainy and dry season flows. In all key water abstraction points, annual and main rainy season QfLULC

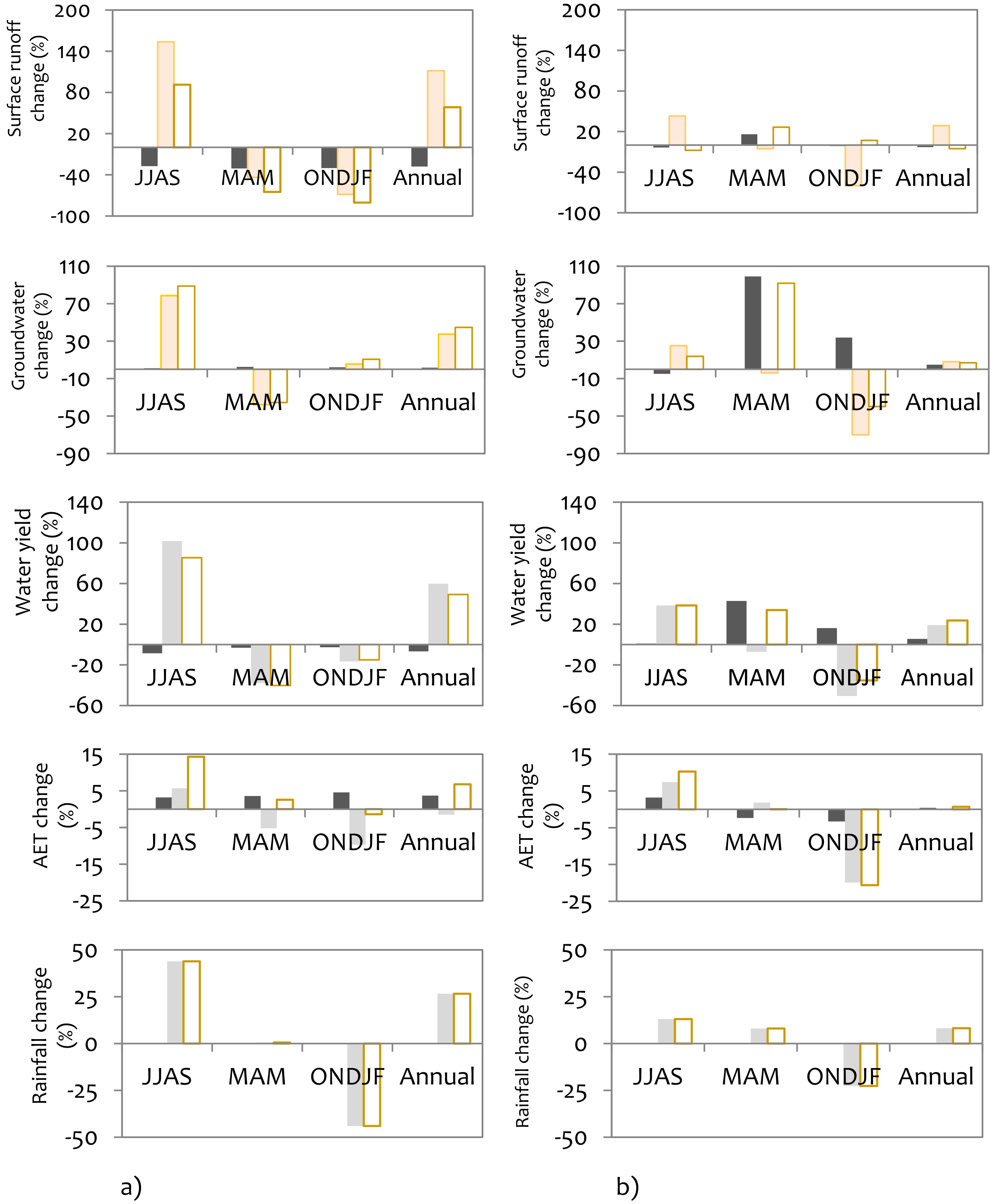


Fig. 4. Changes in average water balance components in the Tana (a) and Beles (b) watersheds between 2010 LULC and future LULC change, future climate change, and future LULC and climate change combined scenarios. Dark bar stands for scenario for changes in land use and land cover, light bar stands for scenarios for changes in climate and hollow bar stands for scenario for combination of both land use and climate changes.

would be lower than Q2010LULC, likely because afforestation might increase the actual evapotranspiration rate, especially when the soil moisture is abundant. The change in streamflow in the small rainy season would reveal mixed states. For instance, at the Ribb abstraction point, QfLULC might be higher than Q2010LULC; but at Megech, Lake Tana, Koga and Gummara B abstraction points, QfLULC would be lower than Q2010LULC. In the dry season, five out of nine key abstraction points in the Tana watershed might show higher QfLULC than that of Q2010LULC. Possible explanation for this is that evapotranspiration from forest land would be constrained by soil moisture availability. It is worth mentioning that the response of the streamflow to LULC change would vary in time and space (Fig. S1).

In the Beles watershed, the influence of fLULC on streamflow would vary among the abstraction points (Fig. 5). At the sub-basin outlet,

Table 3
Basin-scale average annual hydrological components at Tana and Beles watersheds.

Simulations		Hydrological components (mm)							Ratios of water balance components			
		PET	AET	Precipi-tation	Percolation to shallow aquifer	Surface runoff	Lateral flow	Return flow	Streamflow to precipitation	Baseflow to total flow	Surface runoff to total flow	AET to precipitation
Tana	2010 LULC	1652	814	1351	254	168	111	176	0.34	0.63	0.37	0.6
	fLULC	1652	844	1351	258	121	123	179	0.31	0.71	0.29	0.62
	fCC	1744	831	1710	329	355	133	242	0.43	0.51	0.49	0.49
	fLULC & fCC	1744	869	1710	345	266	159	255	0.4	0.61	0.39	0.51
Beles	2010 LULC	1747	773	1552	338	304	193	222	0.46	0.58	0.42	0.5
	fLULC	1747	776	1552	349	294	231	233	0.49	0.61	0.39	0.5
	fCC	1827	770	1683	350	392	225	242	0.51	0.54	0.46	0.46
	fLULC & fCC	1827	778	1683	348	375	277	240	0.53	0.58	0.42	0.46

PET = potential evapotranspiration, AET = actual evapotranspiration.

QfLULC might be significantly higher than that of Q2010LULC on annual and seasonal scales. Increases in lateral and baseflow components seem to be the main contributors to the increase in QfLULC at the outlet of the Beles watershed, even though surface runoff might be slightly reduced (Table 3). On the other hand, the annual and seasonal QfLULC at the irrigation diversion site, Ayima, would consistently decrease (Fig. 5). The differences in response of streamflow to future LULC change at different abstraction points would be due to varied extent of LULC changes upstream of those locations. The area under cultivation with slope higher than 10% is concentrated in the upstream of the watershed area. Both the increase in forest and the decrease in cultivation land might result in a decrease in surface runoff and, hence, in streamflow at the Ayima abstraction point. Woldesenbet et al. (2017a) showed that deforestation and expansion of cultivation land have increased surface runoff over time in the study watersheds.

4.3. Impacts of combined future climate and LULC changes

The response of water-balance components for the combined impact of fLULC and fCC are shown in Fig. 4 for both watersheds. The response of hydrological components under these scenarios would either amplify or be alleviated compared to that under the fCC scenario only (Fig. 4). At the Tana watershed, surface runoff and water yield would be mitigated in the main rainy season and on the annual scale compared to that under fCC. In contrast, lateral flow, groundwater flow, percolation and actual evapotranspiration might amplify under combined scenarios compared to that under the fCC scenario alone. At the Beles sub-basin, the combined scenario might counter-effect the main rainy season surface runoff component but might amplify lateral flow, groundwater flow and actual evapotranspiration for combined scenario.

Seasonal and annual streamflows at the Tana watershed outlet might be offset under concurrent effects of fLULC and fCC compared to sole fCC scenario (Fig. 6). On the other hand, the dry season streamflow at Gilgel Abay A and the small rainy season streamflow at Gummara B might amplify under combined scenarios in comparison to that in fCC alone. Streamflow response under combined fLULC and fCC at the Beles watershed outlet would be amplified compared to under fCC alone, particularly in the small rainy season, in the dry season and on the annual scale. The main rainy season, dry period and annual streamflows response for a concurrent scenario would be lower than that of fCC alone. These varying responses of streamflow to the combined scenario, compared to the fCC alone, at different abstraction points indicate that the LULC change would have a significant influence on streamflow at different spatial scales.

Annual actual evapotranspiration might increase at basin scale under the fCC scenario, and amplify with combined fLULC and fCC scenarios. Simulation under concurrent scenarios of fLULC and fCC would offset the baseflow or surface runoff proportional to total flow when compared to under fCC scenario only. The LULC changes would have a mitigating and amplifying effect in the two watersheds. It is worth mentioning that the wetting trend of near- future GCM-simulated hydrological components might overcome that of the warming trend and, hence, might enhance mean availability of annual and rainy season streamflow.

5. Discussion

The type, the extent, and the location of LULC change in the basin determine the extent of the resulting effect on water balance or basin hydrology. Converting the cultivation land on steep slopes to forest land would reduce main rainy season discharge and increase it in dry period, consequently mitigating flood probabilities in the main rainy season and drought threats in the dry period. This might also reduce land degradation resulting from erosion during rainy season, and enhance water availability for existing and planned irrigation schemes during dry period. However, it must be noted that floods are mostly triggered by precipitation intensities and peak flows and not directly by total precipitation or streamflow. Soil erosion and sediment availability from cultivated fields decreased as rainy season progressed due to increased vegetation cover (Bayabil et al., 2017; Ebabu and Yibeltal, 2018). Descheemaeker et al. (2006) also revealed that expanded vegetation cover due to areas closed off from the interference of human and domestic animals significantly reduced surface runoff in Tigray highlands, Ethiopia. On the other hand, conversion of forest to agricultural land increases surface runoff, which in turn increases sediment

Table 4
Annual average streamflow for different scenario simulations at Tana and Beles sub-basins (m^3/s).

Scenarios/key locations	Megech	Ribb	Gummara B	Gummara A	Gilgel Abay A	Gilgel Abay B	Koga	Jemma	Tana outlet	Ayima	Dangur	Beles outlet
2010 LULC	3.4	16	8.3	9.0	42.4	33.4	4.6	5.7	259.1	13.1	231	306.4
fLULC	2.8	15.7	8.2	8.5	41	32.4	4.2	5.5	222.4	11	235.2	323.1
fCC	4.9	21.6	11.4	12.5	61	77.3	8.1	18.9	426.3	23.3	245.5	363.8
fLULC & fCC	4.1	20.8	10.9	11.8	59.4	75.2	7.5	18.3	359.9	21.3	250.6	377.7

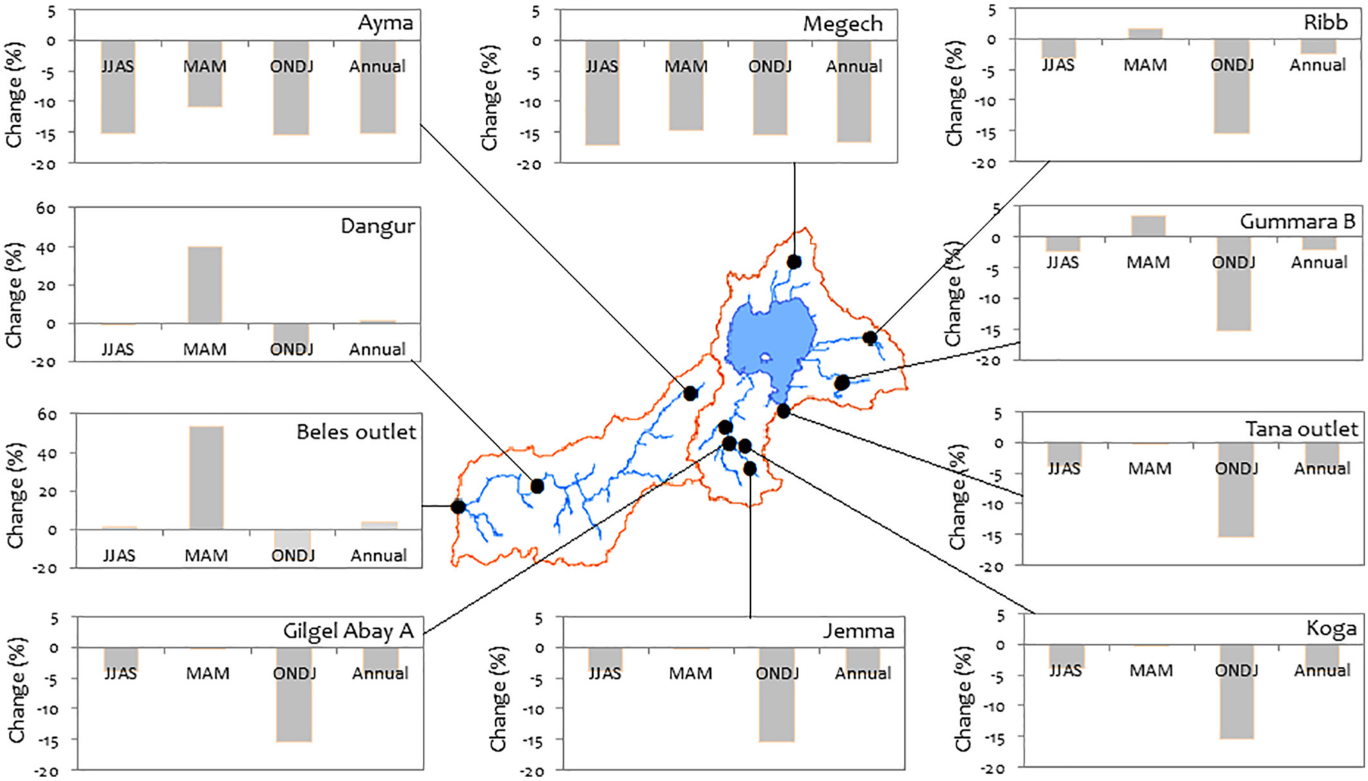


Fig. 5. Changes in annual and seasonal streamflow response to future LULC change scenario relative to that for 2010 LULC at key locations.

concentration in the water and clay hardpan formation, and decreases deep percolation (Tebebu et al., 2017; Steenhuis et al., 2017). In this regards, Tebebu et al. (2015) suggest that revegetation of degraded areas on the steep slopes are crucial to reduce the sediment concentration originating from those areas, which are the main contributors of sediment concentrations.

The change in streamflow in the main rainy season is expected to be much higher than that of annual flow. Therefore, climate change would affect not only the amount of annual average, but also the timing of streamflow. The implication of increased near-future rainfall as simulated by GCMs might exacerbate the extreme flows although historical GCMs-simulated rainfall underestimated the observed rainfall. As a result, the near-future climate might intensify flooding, reservoir siltation and degradation of land by erosion. Nevertheless, erosion is triggered by precipitation intensities than the total rainfall. These results are in accord with those of a previous study in the Blue Nile (e.g. Beyene et al., 2010) which reported that streamflow would increase at least in near future, even though different horizons of future climate were considered. Using six GCMs and two emission scenarios from Special Report on Emission Scenarios (SRES) for the period 2020–2039 on the two tributaries of the Lake Tana, Ayele et al. (2016) reported that increasing runoff would occur due to the increase in precipitation. Based on only one GCM and two old emission scenarios, increased streamflow is also predicted to occur due to future long-term climate change in the upper catchments of the Blue Nile (Fentaw et al., 2018; Melke and Abegaz, 2017; Nigatu et al., 2016). Multi-model and multiple RCP scenarios indicated increased average annual streamflowfor long-term climate change in the upper Blue Nile regions (Wagena et al., 2016; Gebre and Ludwig, 2015; Liersch et al., 2018). Mekonnen and Disse (2018) also showed increases in long-term future temperatures and rainfall in the upper Blue Nile basin using ensemble mean of the six GCM and four RCPs scenarios. However, Elshamy et al. (2009) described how the hydrology of the study region may become drier in the future (2081–2098) due to no change, or only moderate changes in rainfall. In our study, at least for the near-future projections, soil moisture is expected to increase with increased precipitation. Hadgu et al. (2015) indicated that annual total rainfall might remain unchanged, but the main rainy season rainfall might increase in Northern Ethiopia. But Abdo et al. (2009) predicted that rainy season runoff volume for the 2080s horizon would be reduced at the Gilgel Abay watershed. All the aforementioned scholars indicated that future precipitation projections in the Blue Nile basin are not as consistent as temperature, and are affected by high uncertainties.

Common practices to evaluate prediction uncertainties in climate change impact studies include the use of multiple GCMs, different emission scenarios and/or multiple hydrological models (e.g. Bae et al., 2011; Chen et al., 2012; Dams et al., 2015; Najafi and Moradkhani, 2015; Prudhomme et al., 2003). In our case, we applied ensemble average of multiple GCMs, but different emission scenarios and multiple hydrological models were not considered. Nevertheless, others have shown that, for near-future projection, different emission scenarios for a given GCM might result in similar temperature and rainfall projections (Praskievicz and Chang, 2009; Roosmalen et al., 2009; Kirtman et al., 2013). The hydrological model uncertainty was estimated following Abbaspour et al. (2004) using a Sequential Uncertainty Fitting-2 approach (SUFI-2). Behavioral parameter sets were selected based on a Nash-Sutcliffe threshold, such that the prediction envelope for the daily streamflow brackets the observed river flow entirely. Most of the discharge observations at the sub-watersheds outlets for the calibration period are bracketed by the 95% prediction confidence interval (see Fig. S1).

It is worth emphasizing that all GCMs basically produce varying precipitation projections since they represent atmospheric conditions and feedbacks in a different way (Praskievicz and Chang, 2009). For this reason, precipitation simulations from large-scale climate predictors obtained by using downscaling approaches are still a problem in hydrometeorological research (Chen et al., 2012).

Because of the linked seasonal variations in evapotranspiration, expansion in forest cover resulting from replacing cultivation lands with

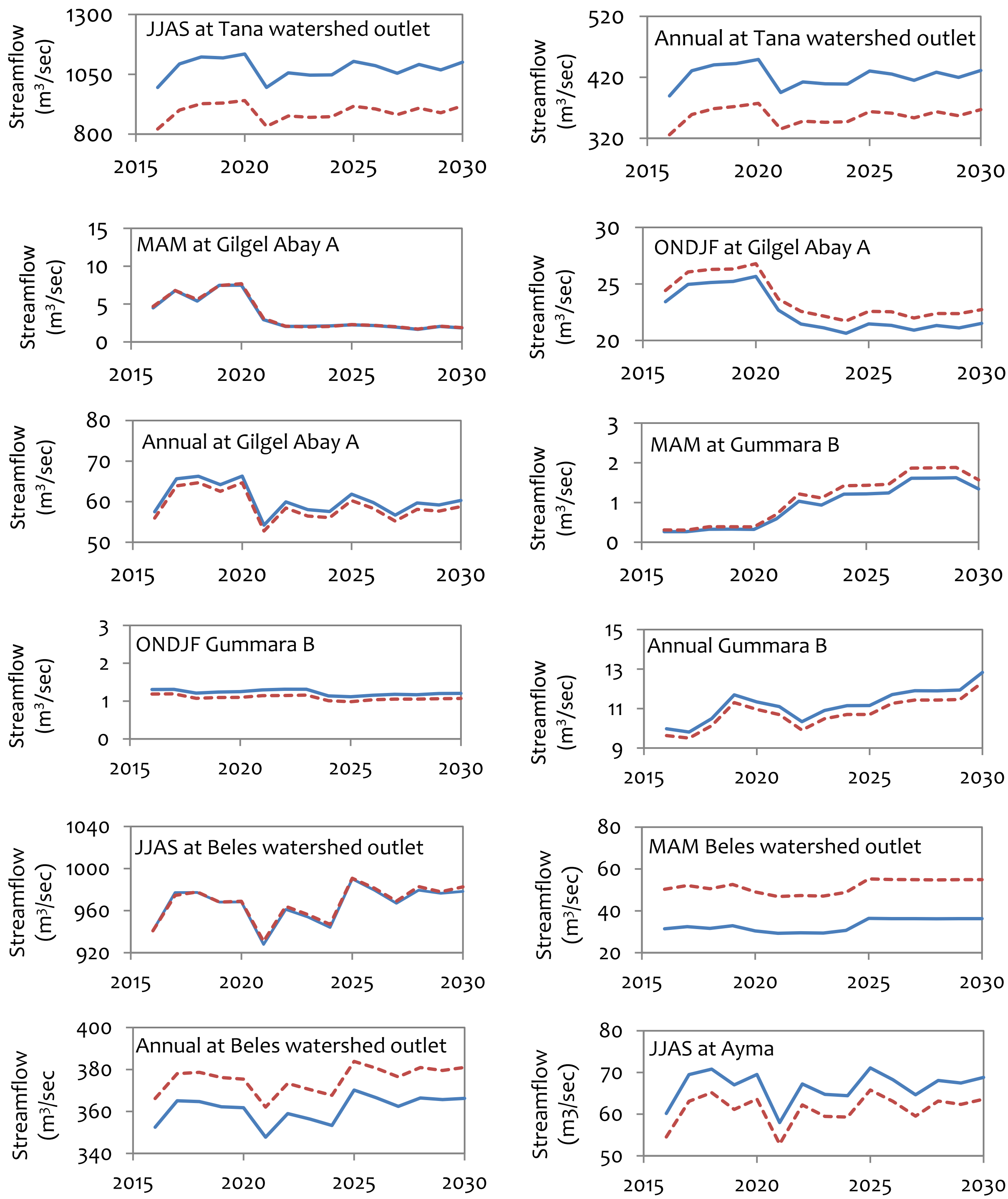


Fig. 6. Comparison of annual and seasonal streamflow responses between future climate change scenario, and combined future climate change and LULC scenario at selected locations. JJAS stands for June, July, August and September. MAM stands for March, April and May. ONDJF stands for October, November, December, January and February. Solid line represents simulated discharge using climate change scenario while broken line stands discharge using both climate and land use changes scenarios.

plantation would reduce (increase) during the wet (dry) season, thus reducing flood (drought) possibilities respectively (see Figs. 7 and 8). Forest plantations in currently cultivated areas can have different outcomes on catchment hydrology based on forest age and development (Brown et al., 2005). Runoff (soil loss) reduces as the forest matures. In the early stage, the soil surface is less covered, subject to higher erosion. However, based on the present study, new eucalyptus plants might cover land surfaces in short time period after plantation. Pit planting system might also reduce runoff (soil loss) than that of furrow planting system. The land around pits might also be left as fallow land which reduce water and soil losses. The important inference from these findings is that it could be possible to alleviate extreme hydrologic regime and land degradation due to future climate change by planning LULC to attain particular hydrological effects on land cover in the watersheds.

Water balance components and streamflow would be more sensitive to climate change than to the LULC changes scenario, even though changes in land use have far-reaching influences on streamflow/water balance components in the study region. The outputs of the response

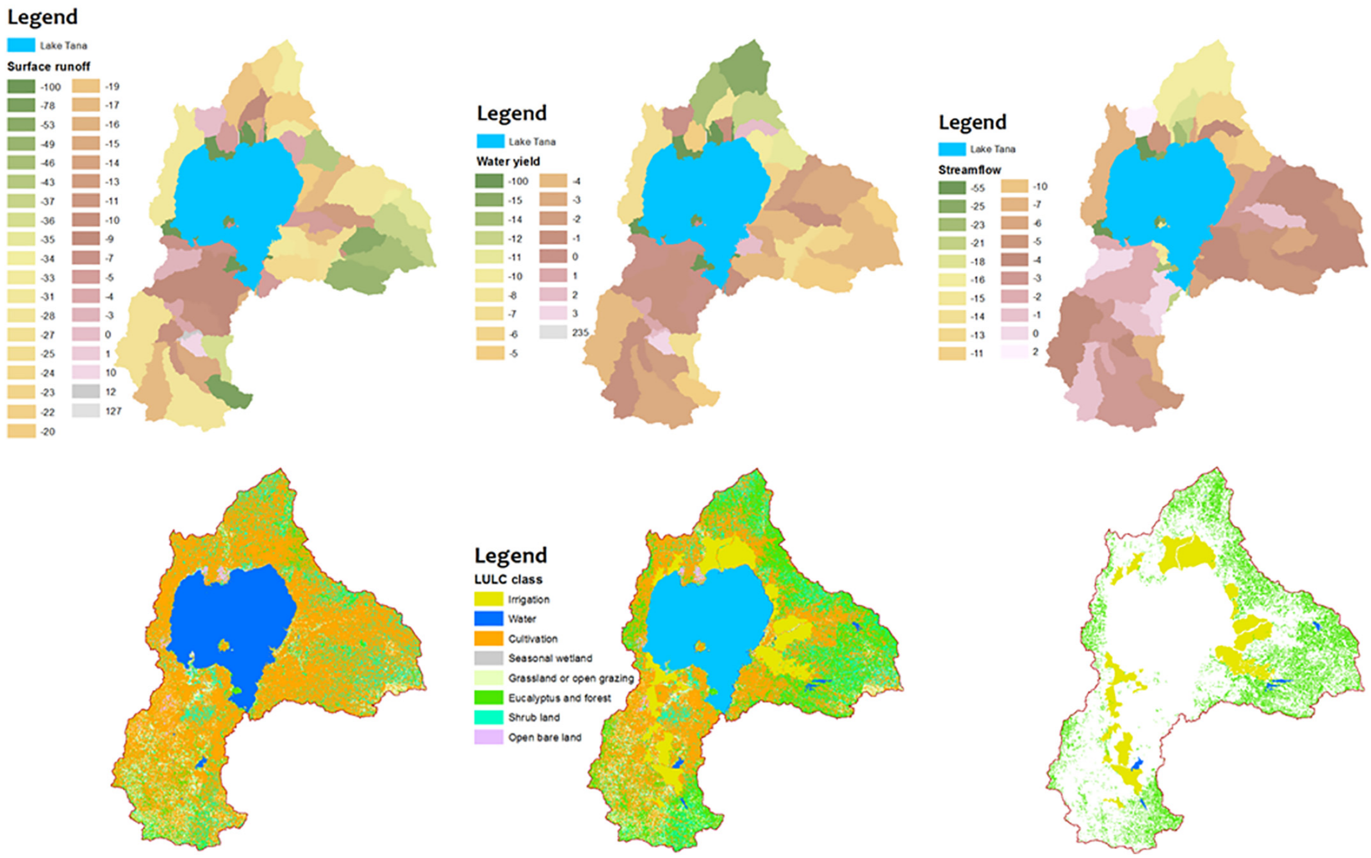


Fig. 7. Spatial distribution of changes in land-use, land-cover and water balance components at Tana watershed. Top panel shows percentage difference between water balance components for future climate change and combined f LULC & fCC scenarios. Bottom left map depicts 2010 land use and land cover, middle lower map represents future land-use and land-cover scenario, lower right figure shows only changed LULC classes in the future land use and land cover scenario with respect to historical LULC. White area in the bottom right panel shows unchanged areas. Percentage changes in the top panel legend categories are in actual magnitude rather than scaled values.

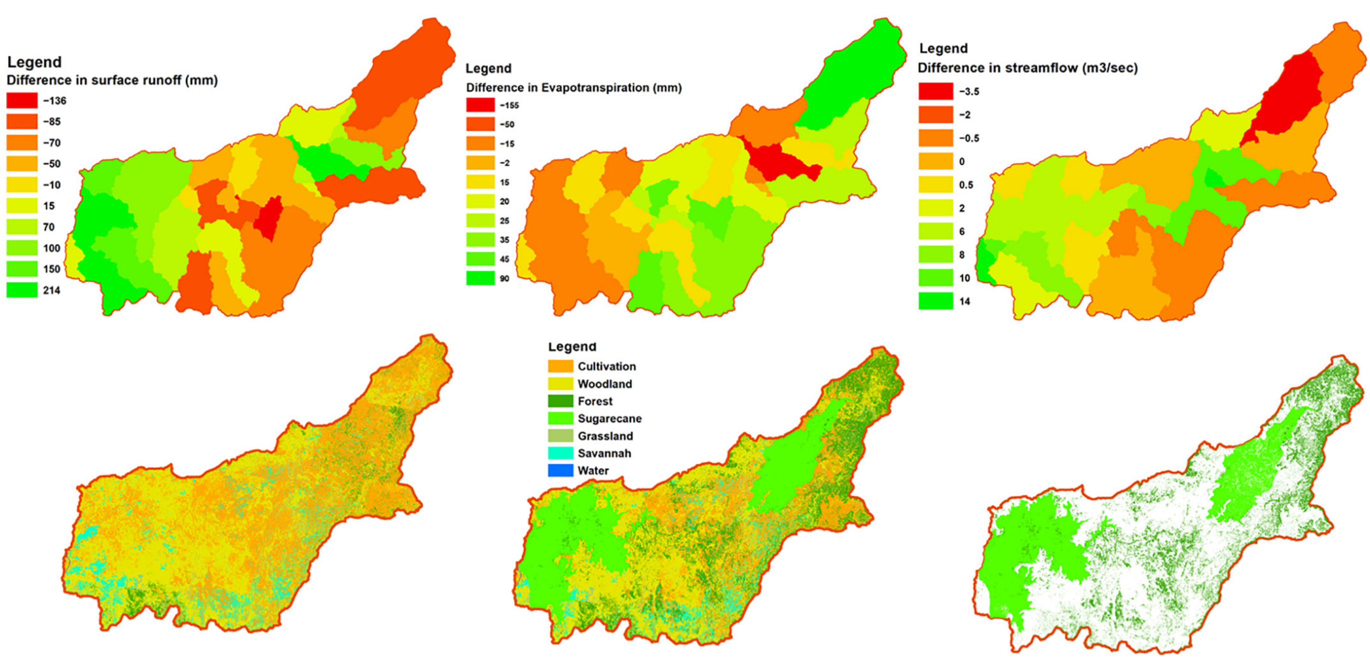


Fig. 8. Spatial distribution of changes in land-use land-cover and water balance components at Beles watershed. Top panel shows percentage change between water balance components for fLULC scenario and 2010 LULC. Bottom left map depicts 2010 LULC, middle lower map represents future LULC scenario, lower right figure shows only changed land-use and land-cover classes in the future LULC scenario with respect to historical LULC. White area in the bottom right panel showed unchanged areas. Percentage changes in the top panel legend categories are in actual magnitude rather than scaled values.

of a catchment to LULC and climate changes might not be uniform. Some studies have noticed that, compared to climate change, LULC change is likely to affect basin hydrology more (e.g. Cuo et al., 2009). Other studies, however, have found that fCC scenarios are more extensive than fLULC scenarios in determining hydrological responses (e.g., Roosmalen et al., 2009). Studies combining both scenarios have reported an increase in runoff (Samaniego and Bárdossy, 2006).

According to Hawkins and Sutton (2009), climate projections are subject to three main sources of uncertainty, such as forcing or emission scenario uncertainty, model-response uncertainty and natural variability. "*In near-term, different scenarios give rise to similar magnitudes and patterns of climate change*" (Kirtman et al., 2013). Therefore, forcing or emission scenario uncertainty is not quantified in the present study. Relative proportion of uncertainty due to internal variability is commonly quantified from multiple ensemble realizations per a GCM model. As downscaled future climate data by MarkSimGCMs documented only one ensemble member per model, the relative contributions of uncertainty due to natural variability for projected near-term climate is not quantified. Uncertainty derived from model-response in the near-future climate change is reported as supplementary information (Figs. S3 and S4).

6. Conclusions

In this study, variations in streamflow and water balance components under different climate and land use change scenarios for the future period 2016–2030 were investigated. The simulation results indicated that streamflow response to simultaneous future LULC and climate change scenarios on the seasonal scale might vary among key water abstraction locations. The wetting trend of near-future GCM simulated hydrological components would exceed that of the warming trend and, thus, might enhance the availability of annual and rainy season streamflow.

Expansion of forest cover after reverting cultivation lands on steep slopes to forest might reduce streamflow and surface runoff in the rainy season and raises it in the dry period, thus diminishing extreme hydrological regime. On the other hand, loss of forests would increase flood potential, and also intensify drought impact. Furthermore, forest loss on steep slope might increase surface runoff, which in turn implies accelerated land degradation.

The combined impacts of climate change and LULC dynamics can be rather different from the effects that follow-on from LULC or climate change alone. The important inference from these findings is that it could be possible to alleviate intense floods or droughts due to future climate change by planning LULCs to attain particular hydrological effects on land cover in the basin. All the findings in this study are only applicable under the aforementioned future climate and land use change scenarios. In reality, a systematic bias was found when the climate data generated from the scenarios were compared to the observed historical climatological data for the base period of 1980–2005. Compared to climate change scenarios, the LULC change scenarios applied in this study are abridged without taking into account land use policy and socio-economic development. The LULC change scenario was set up based on the assumption of more conservation practices in the future in order to reduce erosion and sedimentation. This might not be the actual trend of future LULC change in the study region. It is recommended that future research use land use modeling, which considers socio-economic development and biophysical driving forces, to asses future land use dynamics.

Simulated data from regional climate models, such as CORDEX, might be compared with that of MarkSimGCMs simulated data in order to choose more realistic climate projections which might reduce the uncertainties in future water balance projections. All of these shortcomings may possibly increase the uncertainty of the model outcomes. Notwithstanding that the modeling results have the aforementioned limitations, the outcomes of this study are appropriate, dependable and credible under the present climate change and land use scenarios. Moreover, the techniques are beneficial for evaluating the combined effects of climate and land use changes on basin hydrology. The findings and approach of this study still have significance for natural resources management in the future for the Tana and the Beles watersheds, as well as other regions encountering similar pressures from climate change and LULC dynamics. As land development and change in climate would continue, integrated land and water use planning should be executed to deal with the potential changes of hydrological regime and land degradation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.06.198.

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